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Meta-analysis of studies on eggshell concrete using mixed regression and response surface methodology

Beng Wei Chong [a], Rokiah Othman [a], Ramadhansyah Putra Jaya [b,*], Xiaofeng Li [b], Mohd Rosli Mohd Hasan [c], Mohd Mustafa Al Bakri Abdullah [d]

[a] Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, 26300 Kuantan, Pahang, Malaysia
[b] Department of Civil Engineering, College of Engineering, Universiti Malaysia Pahang, 26300 Kuantan, Pahang, Malaysia
[c] School of Civil Engineering, Universiti Sains Malaysia (Engineering Campus), 14300 Nibong Tebal, Pulau Pinang, Malaysia
[d] Geopolymer & Green Technology, Centre of Excellent (CEGeoGTech), Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia

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ABSTRACT

Eggshell concrete is an innovative green material that helps to recycle eggshell waste while reducing the environmental harm caused by excessive cement production. However, recent studies on eggshell concrete are limited and the outcomes may vary due to the variation of mix design. Design of experiment is used to simplify and optimize the study of sustainable concrete, yet analysis involving eggshell concrete is still scarce. This paper aimed to develop mathematical models for the prediction of eggshell concrete compressive strength using the mixed regression (MR) and response surface methodology (RSM). Overall, 43 datasets were collected from available studies in the literature on eggshell powder as partial cement replacement. The input variables used were percentage of eggshell, percentage of Ground Granulated Blast-furnace Slag (GGBS), cement content, fine aggregate, coarse aggregate, water, and Conplast SP-430 superplasticizer. The analysis of contour plot concluded that eggshell powder increased the concrete compressive strength at an optimal replacement percentage between 5% and 10%. However, the cement partial replacement with eggshell powder is more optimal for mix design with higher water content. The statistical results of the model, such as R^2, adjusted R^2 and root-mean-square error (RMSE), indicated that both MR and RSM models are powerful tools to formulate and predict the eggshell concrete compressive strength. However, RSM models showed better accuracy and lower deviation.

1. Introduction

Cement is a vital product for the construction industry, but the sharp-rising demand for this product has brought forth many challenges, such as the shortage of raw materials and damages to the environment (Naqi and Jang, 2019). Every year, over 10 billion tons of concrete are being produced to cater for the need of modern human civilisation (Meyer, 2004). It is estimated that about 900 kg of carbon dioxide (CO_2) gas is emitted into the environment for every ton of cement production (Benhelal et al., 2013), and the cement industry is accounted for about 7% of the global CO_2 emission (Devi et al., 2018). Apart from being a large contributor of greenhouse gas, the cement industry is also responsible for major air pollution through the release of particulate matter (PM), oxides of nitrogen (NO_x), carbon monoxide (CO), sulphur dioxide (SO_2) and volatile organic compounds (Adeyanju and Okeke, 2019). These pollutants pose a great risk to both the environment and human health (Edalati and Namdari, 2014).

Chicken eggshell waste is a major problem faced by countries with a developed poultry industry (Hassan and Aigbodion, 2015). Eggshell is disposed in large quantity in Malaysia as this country is one of the largest egg consumers in the world (Doh and Chin, 2014). Although eggshell is non-hazardous, it attracts worms and rats which are among the major sources of health problems to the public (Jayasankar et al., 2010). In Malaysia, eggshells are regarded as municipal waste from household and poultry industry, thus most of this waste would end up in the landfill (Chong et al., 2020). In order to promote the reuse of waste materials, the use of eggshell has been introduced as a biodiesel catalyst, absorbent of

* Corresponding author.
E-mail address: ramadhansyah@ump.edu.my (R.P. Jaya).

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heavy metals, fertiliser, and even medical items (Faridi and Arabhosseini, 2018). The overall chemical composition of eggshell is similar to limestone (Chandrasekaran, 2018), making it a potential cement replacement in concrete (Mtallib and Rabiu, 2009). Nevertheless, there are currently limited studies in the literature that looked into the use of eggshell powder as partial cement replacement. In addition, certain studies introduced another replacement material in conjunction with eggshell powder (Jamellodin et al., 2018), making it difficult to determine the real effect of eggshell powder on concrete strength. Besides that, the differences in mix compositions may also affect the effectiveness of eggshell powder as cement replacement.

Recently, Design of Experiment (DoE) techniques such as regression analysis and Response Surface Methodology (RSM) are being applied in the studies on concrete materials. Regression analysis is a basic statistical method that is done to study the correlation between variables. The RSM provides mathematical solutions to a problem, reduces the number of experimental trials, and saves the cost and time used in a study (Boyaci, 2005). It has been applied to provide detailed analysis and accurate estimation of fresh properties (Nambiar and Ramamurthy, 2006; Şimşek et al., 2016; Senthil Kumar and Baskar, 2014), mechanical properties (Alqadi et al., 2013; Oyejobi et al., 2020), and even durability (Vasudevan et al., 2020) of concrete. Busari (2019) applied the RSM analysis to study the properties of concrete with metakaolin and to determine the optimum amount of metakaolin for maximum compressive strength. de la Rosa et al. (2019) studied the behavior of steel-fibre-reinforced concrete for the determination of compressive strength. Senthil Kumar and Baskar (2014) utilised the RSM analysis to optimise concrete with e-waste through a response surface with the percentage replacement and compressive strength. Meanwhile, Hammoudi et al. (2019) used both the RSM and Artificial Neural Network (ANN) methods to study the compressive strength of recycled concrete aggregates. However, while a number of literature are available for the RSM modelling of sustainable concrete properties, the RSM analysis on eggshell concrete is still scarce.

In this study, mixed regression (MR) and RSM models were developed to formulate the eggshell concrete compressive strength. The percentage of eggshell replacement and the amount of each concrete constituent were measured as the variables to predict the 7-day and 28-day compressive strengths. The accuracy and effectiveness of the models were assessed by the determination coefficient (R^2), adjusted coefficient (R^2 adj) and root mean-square error (RMSE). The effect of eggshell powder on the concrete compressive strength was investigated through the contour plot. Finally, the efficacy of both methods in predicting the eggshell concrete compressive strength were compared and discussed.

2. Materials and method

2.1. Eggshell powder

Chicken eggshell powder is being used as cement replacement due to its high calcium content. Eggshell powder will be firstly processed by being washed, dried under the sun or oven, and then crushed or grinded to the desired size. The literature which are used in this study involved eggshell powder with grind size ranging from 75 μm (Gajjar and Zala, 2018) to 90 μm (Kannam Naidu et al., 2018; Yadav and Eramma, 2017; Yerramala, 2014; Imran et al., 2019). The specific gravity measured varied from 2.01 (Yadav and Eramma, 2017), 2.37 (Yerramala, 2014), 2.66 (Kannam Naidu et al., 2018) to 2.89 (Gajjar and Zala, 2018). The chemical compositions of eggshell powder were gathered from a number of past studies and the results were recorded in Table 1. As can be seen, the main compositions of cement are calcium oxide (CaO) and silicon dioxide (SiO_2) which are the essences of the hydration process with the water presence. Eggshell powder contains similar level of calcium oxide, making it a viable material to supply CaO, promote the hydration process and also to serve as partial cement replacement (Shiferaw et al., 2019). The high loss of ignition of eggshell powder is also attributed to its high content of CaO (Oluwatuyi et al., 2018). While ordinary Portland cement (OPC) also contains high content of the same compound, it is generated by heating process and hence has a low loss of ignition. Eggshell does not contain compound that is harmful to concrete, such as chloride.

2.2. Database

Experimental data were gathered from a number of literature that looked into the use of concrete with eggshell as partial cement replacement. As can be seen from the results in Table 2, a total of 43 datasets were collected from seven studies with clear specification of the materials used, mix composition, as well as 7-day and 28-day compressive strengths. For instance, Conplast SP-430 was used as the superplasticizer in one study (Yadav and Eramma, 2017). The database included eggshell concrete mix design of up to 45 MPa which defined the range and limitation of the model. Studies with eggshell powder as the only replacement material were given priority while studies on concrete that combined eggshell and another replacement material were excluded. However, due to the scarcity of literature on eggshell powder replacement alone, studies on eggshell and GGBS were included in the analysis. Unlike other studies involving eggshell powder and another varying material, studies on eggshell powder and GGBS were plenty, which made it possible to include the percentage of GGBS replacement as the predictor of compressive strength. The inclusion of GGBS as a predictor allowed the influence of GGBS to be noted and hence controlled. In addition, the properties of basic concrete constituents such as the type of cement used and the gradation of the aggregate were neglected to focus on influence of eggshell powder on concrete compressive strength.

A total of seven independent variables or predictors were selected, namely eggshell, GGBS, cement, fine aggregate (FA), coarse aggregate (CA), water, and superplasticizer (SP). The outputs of the studies are 7-day and 28-day compressive strengths.

2.3. Mixed regression (MR)

Regression analysis is a basic statistical method that is still widely used to determine the relationship between a single dependent variable and other independent variables. The most basic form of simple linear regression is used to test for linear relationship. However, the regression method can be used to test for other relationships by transformation, as shown in Table 3. Apart from determining the relationship between two variables, the expression for a single dependent variable with many variables can be formulated using MR. In this study, the combination of linear and quadratic relation was used to formulate the model for predicting the eggshell concrete compressive strength.

2.4. Response surface methodology (RSM)

The RSM is a DoE method which evaluates the effect and interaction of multiple variables towards a dependent variable. According to Bradley (2009), the mechanism of the RSM is to understand the topography of the response surface including the local maximum, local, minimum and ridge lines, and also to find the region where the most appropriate response occurs. As shown in Table 4, the first order effect, second order effect and interaction effect

Table 1
Chemical composition of eggshell powder.

Composition (% by mass)	OPC (Yerramala, 2014)	Eggshell powder		
		Kannam Naidu et al. (2018)	Gajjar and Zala (2018)	Yerramala (2014)
Calcium Oxide (CaO)	60.1	52.15	47.49	52.10
Magnesium Oxide (MgO)	2.1	0.60	–	0.06
Silica Dioxide (SiO_2)	21.8	1.22	–	0.58
Alumina (Al_2O_3)	6.6	0.28	0.11	0.06
Ferric Oxide (Fe_2O_3)	4.1	0.16	–	0.02
Chloride (Cl)	–	0.011	–	–
Sulphur Trioxide (SO_3)	2.2	–	0.38	0.62
Potassium Oxide (K_2O)	0.4	–	–	0.25
Sodium Oxide (Na_2O)	0.4	–	0.14	0.15
Loss on Ignition (LOI)	2.4			45.42

Table 2
Mix design from literature.

Sources	No.	Eggshell (%)	GGBS (%)	Cement (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Water (kg/m^3)	SP (%)
Kannam Naidu et al. (2018)	1	0	0	394.4	688	1156	197	0
	2	5	0	394.4	688	1156	197	0
	3	10	0	394.4	688	1156	197	0
	4	15	0	394.4	688	1156	197	0
Parkash and Singh (2017)	5	0	0	375	645	1061.3	150	0
	6	6	0	375	645	1061.3	150	0
	7	12	0	375	645	1061.3	150	0
	8	18	0	375	645	1061.3	150	0
	9	24	0	375	645	1061.3	150	0
Gajjar and Zala (2018)	10	0	0	325	905	1121	159	0
	11	5	25	325	905	1121	159	0
	12	10	25	325	905	1121	159	0
	13	15	25	325	905	1121	159	0
	14	20	25	325	905	1121	159	0
	15	25	25	325	905	1121	159	0
	16	30	25	325	905	1121	159	0
Yadav and Eramma (2017)	17	0	0	399	670	1182	167.58	0.7
	18	7.5	20	399	670	1182	167.58	0.7
	19	7.5	25	399	670	1182	167.58	0.7
	20	7.5	30	399	670	1182	167.58	0.7
	21	7.5	35	399	670	1182	167.58	0.7
	22	10	20	399	670	1182	167.58	0.75
	23	10	25	399	670	1182	167.58	0.75
	24	10	30	399	670	1182	167.58	0.75
	25	10	35	399	670	1182	167.58	0.75
	26	12.5	20	399	670	1182	167.58	0.8
	27	12.5	25	399	670	1182	167.58	0.8
	28	12.5	30	399	670	1182	167.58	0.8
	29	12.5	35	399	670	1182	167.58	0.8
Yerramala (2014)	30	0	0	300	750	1170	180	0
	31	5	0	300	750	1170	180	0
	32	10	0	300	750	1170	180	0
	33	15	0	300	750	1170	180	0
	34	15	15	300	750	1170	180	0
Imran et al. (2019)	35	0	0	360	798	882	158	0
	36	5	5	360	798	882	158	0
	37	10	10	360	798	882	158	0
	38	15	15	360	798	882	158	0
	39	20	20	360	798	882	158	0
Eramma (2019)	40	0	0	437	633	1083.76	197	0
	41	5	0	437	633	1083.76	197	0
	42	10	0	437	633	1083.76	197	0
	43	15	0	437	633	1083.76	197	0

between the variables are considered in the RSM to formulate a respond surface which determines the optimum condition for the dependent variable.

In this study, the constituent material of concrete and the percentage of eggshell powder replacement were measured as the variables. 43 sets of data were collected from seven studies, and the range of each variable is shown in Table 5. While most RSM models use the Central Composite Design (CCD) to collect data in a certain arrangement (Awolusi et al., 2019; Hammoudi et al., 2019; Gajjar and Zala, 2018), this study performed the modelling using uncoded variables. The reason for such difference is that the datasets were collected from different series of experiment and hence not organized in the ideal manner for the said method. The CCD requires three levels for each variable, while the data collected from other past studies had more and varying levels. The significance of the model was evaluated based on quantitative fac-

Table 3
L-4 orthogonal array.

Types of regression	Expression	Dependent variable	Independent variable
Linear	$y = mx + c$	y	x
Second-order polynomial	$y = Ax^2 + Bx + C$	y	x, x^2
Exponential	$y = Ae^x$	$\ln(y)$	x
Logarithmic	$y = Ax^b$	$\ln(y)$	$\ln(x)$
Mixed	Combination of the above		

Table 4
General expression of the RSM for two independent variables.

Effect	Term
Intercept/constant	B_0
First order	B_1x_1, B_2x_2
Second order	$B_{11}x_1^2, B_{22}x_2^2$
Interaction	$B_{12}x_1x_2$
General Expression	$y = B_0 + B_1x_1 + B_2x_2 + B_{11}x_1^2 + B_{22}x_2^2 + B_{12}x_1x_2$

Table 5
Range of the variables for the RSM.

Variables	Lower bound	Upper bound
Eggshell (%)	0	30
GGBS (%)	0	35
Cement (kg/m^3)	300	437
Fine aggregate (kg/m^3)	633	905
Coarse aggregate (kg/m^3)	882	1182
Water (kg/m^3)	150	197
Superplasticizer (%)	0	0.80

tors such as the determination coefficient (R^2), adjusted coefficient (R^2 adj) and RMSE. Qualitative information such as the Patero Chart, residual plot, interaction plot and deviation plot were analysed to provide more information of the model. Lastly, the contour plot was constructed to investigate the impact of eggshell powder replacement on the concrete compressive strength.

3. Results and discussion

3.1. Mixed regression

The concrete compressive strength was modelled using multiple non-linear regressions, or also called as MR. In MR, the relationship between each variable and the dependent variable may be different, and one or more variables possess a non-linear relationship with the concrete compressive strength. The equations generated from the MR are shown below:

$$7DS = 739 + 0.094ESP - 0.006ESP * ESP - 0.028GGBS - 0.035Cement + 0.056FA - 0.057CA - 8.3Water + 0025Water * Water + 32.37SP \quad (1)$$

$$28DS = -794 + 0.075ESP - 0.004ESP * ESP + 0.054GGBS + 0.34Cement + 0.076FA + 0.053CA + 7Water - 0021Water * Water - 18.86SP \quad (2)$$

Table 6 presents the MR model for 7-day compressive strength. With the exception of eggshell (ESP) and GGBS, all the terms in the model had p-value less than 0.05, implying their significance to the dependent variables. The higher p-values for ESP and GGBS are understandable, since the impact of replacement material on concrete strength is lower than the mix design of the main concrete constituents. Moreover, the relationship between eggshell powder replacement percentage and compressive strength was not linear, a parabolic instead, in the model, which agreed with the conclusion of other studies of eggshell concrete (Chong et al., 2021). The R^2 value for the model was 0.8923, which implies a strong correlation ($R^2 > 0.80$) between the selected variables and the compressive strength. Table 7 presents the model for 28-day compressive strength. Since the same set of variables were used, all the terms in the model, except for the replacement materials, were also found to be significant to the dependent variables, The R^2 value of the 28-day model was 0.9170, which is higher than the one of the 7-day model. The RMSE values were 1.749 and 1.990 for 7-day and 28-day compressive strength respectively. The predicted values were computed using the equation obtained from the MR model, and the comparisons between predicted and actual values are tabulated in Table 10. The graphical representation of the actual versus predicted values is shown in Fig. 1 for 7-day compressive strength and Fig. 2 for 28-day compressive strength. As can be seen from the graphs, the distribution of the points fell closely to each other along the $y = x$ axis, indicating that the predicted and actual values did not differ by a large amount. However, certain readings had a larger deviation from the axis, which means that the models are not very accurate particularly for eggshell concrete with lower compressive strength.

Table 6
The MR model for 7-day compressive strength.

Source	Standard error	t-Stat	P-value
Intercept	227.58	3.25	0.003
ESP	0.14	0.68	0.503
ESP*ESP	0.01	−1.13	0.265
GGBS	0.05	−0.05	0.959
Cement	0.04	−0.88	0.386
FA	0.01	7.40	0.000
CA	0.01	−6.99	0.000
Water	2.47	−3.36	0.002
Water*Water	0.01	3.43	0.002
SP	6.27	5.16	0.000
RMSE	1.749		
R^2	0.8923		
R^2 adj	0.8629		

3.2. Response surface methodology

The RSM analysis was conducted using the backward elimination method with α = 0.05. Backward elimination is the simplest variable selection strategy in prediction model building. The method included all variable in the initial model. The least significant variable was then removed and the analysis was repeated until all remaining model had significant contribution to the out-

Table 7
The MR model for 28-day compressive strength.

Source	Standard error	t-Stat	P-value
Intercept	258.92	−3.07	0.004
ESP	0.16	0.47	0.638
ESP*ESP	0.01	−0.66	0.513
GGBS	0.06	0.88	0.385
Cement	0.05	7.51	0.000
FA	0.01	8.89	0.000
CA	0.01	5.67	0.000
Water	2.81	2.49	0.018
Water*Water	0.01	−2.50	0.017
SP	7.14	−2.64	0.012
RMSE	1.990		
R^2	0.9170		
R^2 adj	0.8944		

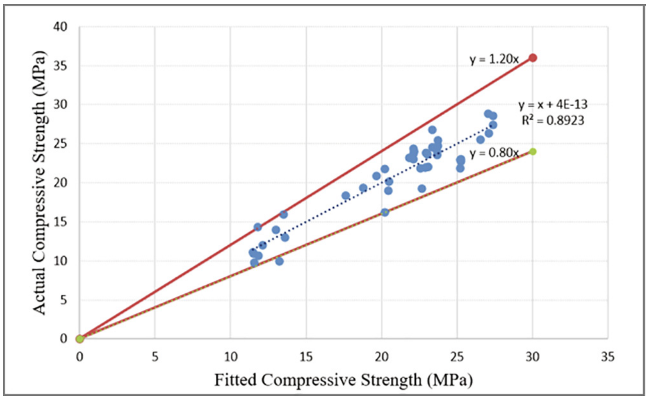

Fig. 1. Actual versus predicted 7-day compressive strength from MR.

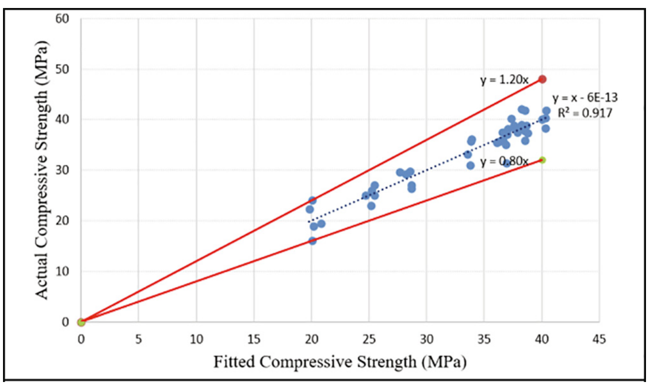

Fig. 2. Actual versus predicted 28-day compressive strength from MR.

come (Chowdhury and Turin, 2020). This method prevented the exclusion of the interaction factor of a variable when the variable by itself was determined to be insignificant. Since this study involved only seven variables, it was paramount to consider as many factors as possible so that the model could utilise the information from all measurements in practical applications of concrete strength prediction. The weakness of backward elimination was that it did not consider the possibility that a dropped variable might become significant later, but this weakness only happened in more complex modelling.

The magnitude of each factors is shown on the Pareto Chart in Fig. 3. The most significant factor in both 7-day and 28-day compressive strengths is the cement content (C). The linear term for the main concrete constituents, such as cement (C), fine aggregate (D), coarse aggregate (E), and water (F) were all significant towards the concrete strength at both periods. The percentage of eggshell replacement (A) was also deemed significant. Interaction terms, such as AA, AE and AF, were high on the list for both cases. Overall, the major factors influencing concrete compressive strength at seven days and 28 days were found to be very similar. The residual versus order plot in Fig. 4 is used to check for the adequacy of the variables in predicting the concrete compressive strength. A shift or trend in the plot indicates the existence of other variables which are not included in the model and has caused an interaction with the distribution of the residue (Yang, 2012). As can be seen from Fig. 4, the residuals of both models were distributed in a zig-zag pattern and no significant trend were observed. This means that there is no other significant factor which was not accounted for in the analysis.

RSM expresses the relationship between independent variables and dependent variables at up to second-order polynomial regression with consideration to the interaction effect of every variable. The equations for 7-day and 28-day compressive strengths are shown below:

$$\begin{aligned}7DS = {} & -202.6 - 0.80ESP - 0.09GGBS + Cement + 0.037FA \\ & - 0.055CA + 0.39Water + 68.59SP - 0.026ESP * ESP \\ & - 0.0013Cement * Cement - 72.7SP * SP + 0.015ESP \\ & * GGBS + 0.0037ESP * Cement + 0.0022ESP * CA \\ & - 0.014ESP * Water - 0.20GGBS * SP \end{aligned} \tag{3}$$

$$\begin{aligned}28DS = {} & 84.2 - 2.25ESP - 0.057GGBS + 0.086Cement \\ & - 0.35FA - 0.019CA + 0.28Water + 92.9SP \\ & - 0.032ESP * ESP + 0.00026FA * FA - 111.2SP * SP \\ & + 0.027ESP * GGBS + 0.0077ESP * Cement \\ & + 0.0032ESP * CA - 0.021ESP * Water - 0.42GGBS \\ & * SP \end{aligned} \tag{4}$$

Tables 8 and 9 show the results from the ANOVA and RSM regression analysis for 7-day and 28-day compressive strengths. ANOVA is used to evaluate the representation of the relationship between predictors and independent variables. The results for 7-day and 28-day models showed p-values of less than 0.001. This indicates that both models were highly significant. The R^2 values for 7-day model and 28-day model were 0.9788 and 0.9817 respectively. R^2 value above 0.90 and close to 1 indicates that the correlation between the variables are high (Moraes, 2012), and over 97% of the variance in the data can be explained by the predictors. Similarly, the adjusted R^2 for both models were above 0.90, indicating a strong fitness of the models. Further investigation of the models

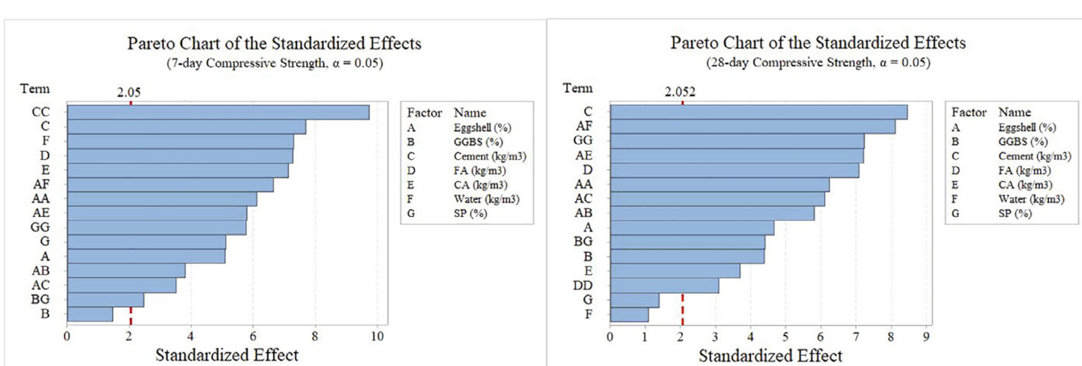

Fig. 3. Pareto chart of the RSM.

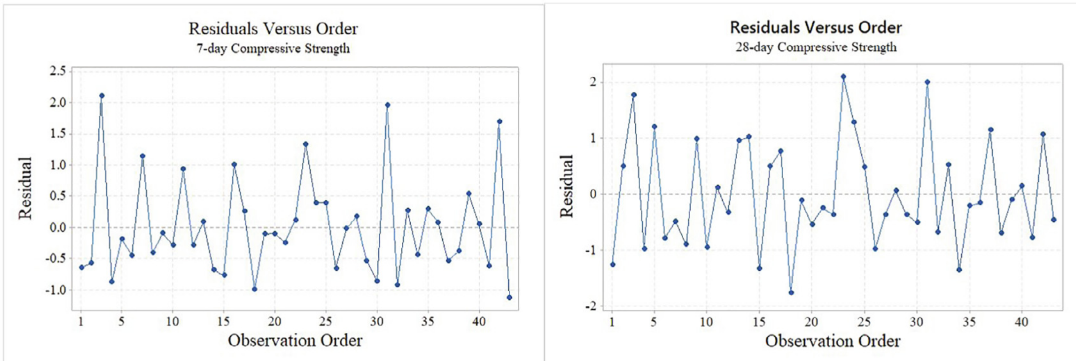

Fig. 4. Residual versus order plot of the RSM.

Table 8
RSM regression model for 7-day compressive strength.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	15	1195.44	79.6958	83.27	0.000
Linear	7	650.21	92.8867	97.05	0.000
ESP	1	24.88	24.8833	26.00	0.000
GGBS	1	2.05	2.0497	2.14	0.155
Cement	1	56.88	56.8828	59.43	0.000
FA	1	51.01	51.0108	53.30	0.000
CA	1	48.78	48.7804	50.97	0.000
Water	1	51.08	51.0793	53.37	0.000
SP	1	25.02	25.0205	26.14	0.000
Square	3	141.09	47.0290	49.14	0.000
ESP*ESP	1	35.78	35.7754	37.38	0.000
FA*FA	1	91.10	91.1049	95.19	0.000
SP*SP	1	31.92	31.9186	33.35	0.000
2-Way Interaction	5	54.93	10.9861	11.48	0.000
ESP*GGBS	1	13.79	13.7908	14.41	0.001
ESP*Cement	1	11.92	11.9151	12.45	0.002
ESP*CA	1	32.22	32.2237	33.67	0.000
ESP*Water	1	42.44	42.4365	44.34	0.000
GGBS*SP	1	5.88	5.8815	6.15	0.020
Error	27	25.84	0.9571		
Total	42	1221.28			
RMSE	0.9783				
R^2	0.9788				
R^2 adj	0.9671				

Table 9
RSM regression model for 28-day compressive strength.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	15	2015.33	134.355	96.55	0.000
Linear	7	739.44	105.635	75.91	0.000
ESP	1	30.34	30.338	21.80	0.000
GGBS	1	26.89	26.893	19.32	0.000
Cement	1	99.68	99.678	71.63	0.000
FA	1	70.07	70.074	50.35	0.000
CA	1	18.95	18.948	13.62	0.001
Water	1	1.66	1.661	1.19	0.284
SP	1	2.73	2.727	1.96	0.173
Square	3	94.58	31.526	22.65	0.000
ESP*ESP	1	54.35	54.351	39.06	0.000
FA*FA	1	13.38	13.379	9.61	0.004
SP*SP	1	72.75	72.754	52.28	0.000
2-Way Interaction	5	129.98	25.996	18.68	0.000
ESP*GGBS	1	47.12	47.123	33.86	0.000
ESP*Cement	1	52.11	52.111	37.45	0.000
ESP*CA	1	72.59	72.589	52.16	0.000
ESP*Water	1	92.01	92.007	66.11	0.000
GGBS*SP	1	27.03	27.028	19.42	0.000
Error	27	37.57	1.392		
Total	42	2052.90			
RMSE	1.180				
R^2	0.9817				
R^2 adj	0.9715				

Table 10
Experimental and statistically predicted values.

No.	Compressive strength (7 days)			Compressive strength (28 days)		
	Experimental	MR	RSM	Experimental	MR	RSM
1	23.7	23.011	24.343	33.18	33.574	34.449
2	24.59	23.333	25.170	35.70	33.850	35.202
3	26.81	23.360	24.705	36.14	33.931	34.364
4	22.07	23.093	22.949	30.96	33.816	31.934
5	10	13.227	10.183	23	25.162	21.795
6	13	13.578	13.450	25	25.471	25.788
7	16	13.505	14.858	27	25.497	27.489
8	14	13.007	14.406	26	25.241	26.898
9	12	12.085	12.095	25	24.704	24.016
10	16.29	20.188	16.571	31.33	36.950	32.274
11	19	20.441	18.068	35.92	38.566	35.796
12	20.23	20.468	20.521	38.81	38.646	39.140
13	21.77	20.201	21.682	41.85	38.531	40.892
14	20.87	19.639	21.553	42.08	38.220	41.053
15	19.36	18.782	20.131	38.29	37.714	39.622
16	18.43	17.630	17.419	37.1	37.011	36.599
17	23.22	21.804	22.964	37.53	36.586	36.751
18	24.07	22.122	25.068	38.07	37.999	39.833
19	24.36	22.108	24.470	38.96	38.267	39.071
20	23.77	22.094	23.871	37.77	38.535	38.309
21	23.03	22.081	23.273	37.3	38.803	37.547
22	24.72	23.717	24.606	38.22	37.073	38.582
23	25.47	23.703	24.140	40.15	37.340	38.049
24	24.07	23.690	23.674	38.8	37.608	37.516
25	23.6	23.676	23.207	37.47	37.876	36.983
26	22.8	25.239	23.458	35.4	36.097	36.377
27	23.1	25.225	23.124	35.7	36.365	36.073
28	22.96	25.211	22.790	35.84	36.633	35.770
29	21.92	25.197	22.455	35.1	36.900	35.466
30	11.1	11.478	11.959	22.30	19.800	22.808
31	14.4	11.800	12.440	24	20.076	21.989
32	10.7	11.827	11.630	18.9	20.157	19.577
33	9.8	11.560	9.528	16.1	20.042	15.575
34	11	11.519	11.446	19.4	20.845	20.763
35	28.84	27.052	28.541	29.6	27.649	29.805
36	28.6	27.361	28.521	29.2	28.194	29.353
37	27.4	27.374	27.935	29.8	28.542	28.651
38	26.4	27.093	26.783	27	28.695	27.698
39	25.6	26.517	25.065	26.4	28.652	26.496
40	21.85	22.567	21.793	40	40.051	39.857
41	22	22.889	22.620	40.3	40.328	41.071
42	23.85	22.917	22.155	41.77	40.408	40.694
43	19.27	22.649	20.400	38.26	40.293	38.725

revealed that every term in the model was highly significant with p-value below 0.05, except for GGBS in the 7-day model and SP in the 28-day model. This is acceptable as both variables were not primary factors in the study, and not every experimental set included GGBS replacement or the usage of superplasticizer. The RMSE values for both 7-day and 28-day compressive strength models were 0.9783 and 1.180 respectively. The error was minor and hence the models' performance was deemed to be satisfactory.

With respect to the equation, the predicted value of compressive strength and the actual compressive strength is tabulated in Table 10. To evaluate whether the error falls within the acceptable range, the a-20 index was adopted (Asteris and Mokos, 2020). Originally proposed to evaluate the error of ANN, this parameter can be applied similarly to other prediction models.

$$a - 20index = \frac{M_{20}}{M} \tag{5}$$

where M20 is the number of samples in which the ratio of predicted value and actual value falls within the range of 0.80 to 1.20 and M is total number of experiment sets. In short, the a-20 index measures the percentage of data with deviation within ±20%. The graphs for actual compressive strength against predicted compressive strength were plotted as shown in Figs. 5 and 6, and the function y = 1.20x and y = 0.80x represented the ±20% deviation. As observed, all the

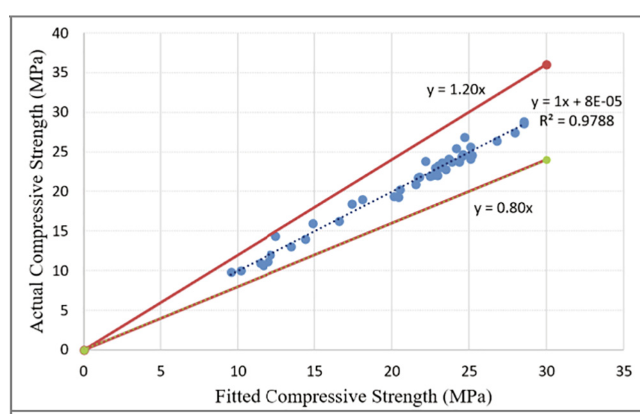

Fig. 5. Actual versus predicted 7-day compressive strength from the RSM.

data points fell within the stipulated zone, indicating a perfect a-20 index of 1. This indicates that both models can be used to predict the eggshell concrete compressive strength with great consistency and limited error.

Interaction plots for the models were presented in Fig. 7. The interaction plot demonstrates how each predictor affects the value

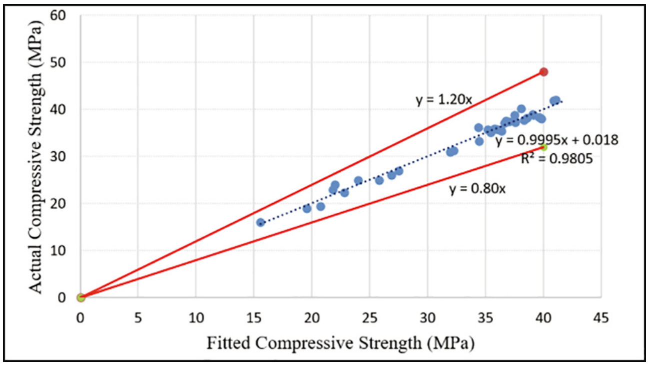

Fig. 6. Actual versus predicted 28-day compressive strength from the RSM.

of the independent variable. As can be seen, the percentage of eggshell powder replacement indicated a curvilinear relationship with the concrete compressive strength. The concrete compressive strength increased with the increase of eggshell powder up to a certain optimal content and decreased steadily beyond the optimal value. GGBS had a minor favourable effect on the concrete compressive strength, while cement and fine aggregate increased the strength. Higher water content was helpful for early strength gain but negatively affected the 28-day strength. Superplasticizer behaved similarly as the eggshell powder, with the optimal content of superplasticizer fell around the mid-point of 0.40% by the cement weight.

The RSM analysis also generates the contour plot which can be used to study the effect of two variables at a given time in a more detailed manner. The contour plot for the percentage of eggshell powder with the percentage of GGBS and water content were generated (Fig. 8) in order to explore the effect of eggshell powder replacement on the concrete compressive strength, at the fixed design mixture, the concrete compressive strength increased at a region close to 5% eggshell powder. A parabolic contour curve of around 41 MPa for seven days and 50 MPa for 28 days were presented in the range of 0% to 10% eggshell replacement. However, beyond 10%, the concrete compressive strength fell with higher

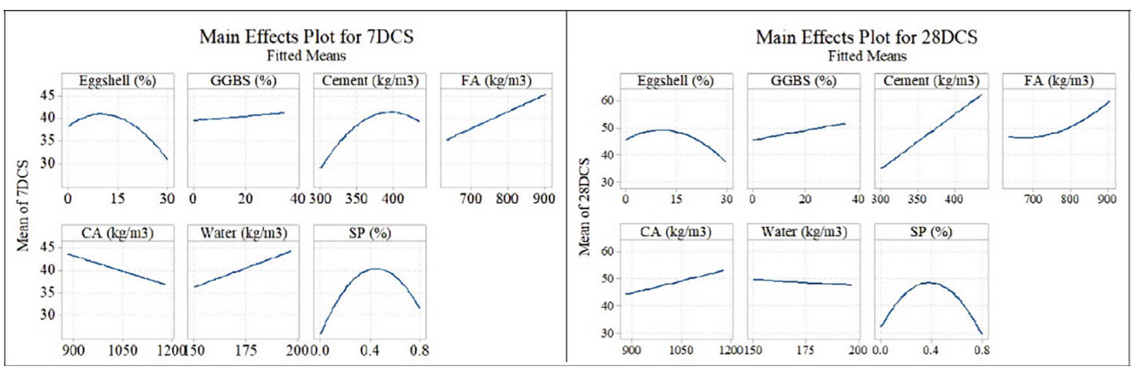

Fig. 7. Interaction plot of the RSM.

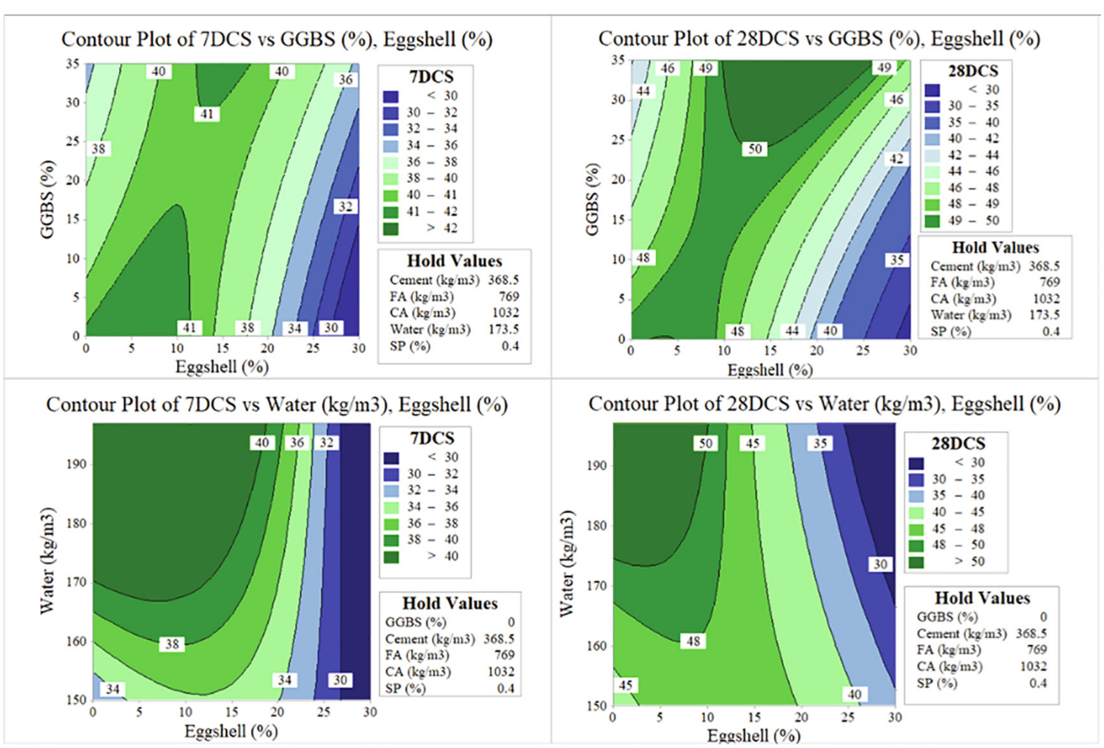

Fig. 8. Contour plot of the RSM.

Table 11
Experimental and statistically predicted parameters.

Parameter	7 days compressive strength		28 days compressive strength	
	MR	RSM	MR	RSM
R^2	0.8923	0.9788	0.917	0.9817
R^2 adj	0.8629	0.9671	0.8944	0.9715
RMSE	1.749	0.9783	1.990	1.180
a-20 Index	0.953	1.0	1.0	1.0

percentage of eggshell powder replacement. This indicates that the cement replacement with eggshell powder improves the compressive strength up to around 5%. Similarly, as can be seen in the contour plot for the percentage of eggshell powder with water content, the concrete has the highest compressive strength at a region with around 5% to 10% eggshell powder. However, the curve centred on the upper part of the contour plot where water content is higher. This may indicate that the positive influence of eggshell powder on concrete compressive strength is stronger on concrete mix design with a higher water content. Since eggshell powder has strong water absorption (Jhatial et al., 2019), it may the absorb the water required for proper hydration in mix design with lower water content.

3.3. Comparison between MR and RSM models

The performance of MR and RSM models were compared through a few parameters as shown in Table 11. At seven days, the R^2 of the MR model was lower than the value in the RSM model, which is 0.8923. Regardless, such value is still considered to be highly satisfactory, and hence all the developed models were deemed reliable in representing the datasets. The RSM models showed higher R^2 and adjusted R^2 values compared to the MR models. In addition, the RSM models had lower RMSE values compared to the MR model for both 7-day and 28-day compressive strengths. The a-20 index of the RSM models showed a perfect 1.0, meaning that all 43 predicted values fell within the range of ±20% of the actual values. For the MR model, 2 out of 43 predictions have error beyond the boundary, resulting in a lower index of only 0.953. To conclude, both the MR and RSM are capable of producing a high quality model for the prediction of eggshell concrete compressive strength, but the RSM is observed to be the better methodology to be adopted.

4. Conclusions

In the present study, the 7-day and 28-day eggshell concrete compressive strengths were modelled using the MR and RSM. The input variables used were the percentage of replacement and the amount of cement, fine aggregate, coarse aggregate, water, and superplasticizer. Based on the results, it is concluded that cement partial replacement with eggshell powder increases the concrete compressive strength. The optimal percentage of replacement for eggshell powder fell around 5% to 10%. However, the positive effect of eggshell powder replacement is stronger at mix design with higher water content to cater for water absorption of the eggshell powder. The study shows that both the MR and RSM models have a great performance in developing a model to predict the eggshell concrete compressive strength effectively. However, due to the nature of the database, the model is valid up to M45 concrete as there is currently no known literature on high-strength or high-performance eggshell concrete. The database also may not represent the properties of nano-eggshell concrete as the analysis is based on micro-eggshell literature. Based on the comparison of both methods, the RSM model was found to be a better method than the MR model with a higher R^2 value and lower error.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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